Improving the sustainability of concrete

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The built environment is a major contributor to CO_2 emissions accounting for approximately 50% of global emissions. To reduce impact, all aspects of construction need to be investigated. Concrete is utilized in infrastructure globally and contributes to industry emissions. Cement, a primary constituent of concrete, is manufactured worldwide and production continues to increase, especially in developing countries. The process is energy intensive and uses both raw materials and nonrenewable fuels, with large amounts of CO_2 emissions emitted during production. To increase the sustainability of concrete, a variety of innovations need to be adopted, from the raw materials used, methods of manufacturing, design and construction, to the end of life phase. The presented work briefly explores various methods aimed at reducing the impact of concrete and increasing the sustainability of the material and the built environment. Drastic changes are needed if we are to meet our 2050 emissions targets.

1 Introduction

Sustainability is a key focus in construction and the materials used are examined using a broader scope that addresses the full life cycle of the product. The main motivation for industrial change is to reach carbon emission targets by 2050 (UN, 2015). As a central material for infrastructure in the built environment, concrete is increasingly investigated to evaluate and address issues of sustainability. The energy consumed by the operation and maintenance of a building accounts for 80-90% of the embodied energy, therefore the embodied energy of concrete is typically neglected. While the embodied energy of concrete per kilogram is low, it is typically used in large quantities, which leads to considerable environmental impact, mainly from cement.

Cement is the primary component of concrete and the energy used in manufacturing accounts for approximately 98% of the embodied energy, approximately 3.9 GJ per ton (IEA, 2010). Moreover, the production of cement generates a substantial amount of greenhouse gases (GHG) with approximately one ton of cement producing one ton to one and a quarter tons of CO_2. In 2008, cement production accounted for 19% of industrial carbon emissions (Allwood and Cullen, 2012). As a key constituent in concrete, the associated impacts of cement manufacturing needs to be addressed.

The amount of cement produced globally is increasing, particularly in developing regions, such as Asia, Latin America and Africa, where major growth and development of infrastructure is occurring. In 2014, worldwide production of cement was approximately 4.2 billion metric tons and the high scenario predicts production to increase to 4.6 billion metric tons by 2050 (USGS, 2015; IEA, 2010). To address the impacts of the concrete, the industry requires significant innovation across the value chain of the material. The presented work will explore the sustainability of concrete through manufacturing, design and construction, and end of life.

2 Manufacturing

Cement is manufactured in an energy intensive process that is typically classified into three stages: raw materials, pyro-processing, and finishing. Limestone is the primary raw material, combined with other raw materials, such as sand, shale, clay and iron ore, also obtained from mines or quarries. The second stage is the clinker production or pyro-processing, which is either a wet or dry process and is the most energy intensive phase. In pyro-processing, a series of chemical reactions occur in the kiln due to the exposure of the raw mix to high heat to form clinker. Once the moisture in the mix is evaporated, the calcination process occurs with calcium carbonate ($CaCO_3$) forming calcium oxide (CaO). The calcium oxide (CaO) then reacts with the silica and aluminum and iron ore to form the liquid phase, or slag. Finally the clinker is formed at the end of the kiln along with evaporation of the volatile components such as sulfates. A dry process kiln is more thermally efficient and utilizes a pre-heater, along with a precalciner, to heat the mix before the material enters the kiln (Choate, 2003). The third and final stage of the cement process is the blending and grinding phase, in which additives, such as gypsum to prevent premature setting, are added.

The three stages all consume energy from various sources, such as nonrenewable fuels or grid-based electricity. The pyro-processing stage, utilizes the majority of energy (~74%). To achieve the high levels of heat required in the kiln, non-renewable fuels, such as coal, petroleum coke, and natural gas are typically used (Choate, 2003). In addition to the high embodied energy, the use of non-renewable fuels contributes to the overall emissions of the manufacturing process.

2.1.1 Efficiency and Emissions

While the efficiency of cement manufacturing has increased significantly, the kiln and pyro-processing stage undergoes large energy losses through the exit flue gases and is also highly inefficient in that one-third of the mass of the limestone is lost in the kiln through formation of carbon dioxide. The emissions from the kiln stage (calcination process and the fuel combustion combined) account for approximately 90% of the CO_2 emissions (Aranda-Usón et al., 2013). Carbon capture and sequestration (CCS) is key to reducing the overall impact of cement. Post-combustion CO_2 capture technology is under development and would significantly reduce emissions (IEAGHG, 2014). In addition to CCS, the industry is exploring other ways to offset the impact of manufacturing including use of substitute fuels. The sections below briefly discuss these topics.

2.1.2 Substitute Fuels

The energy intensive process of the kiln consumes a large amount of typically non-renewable fuels. The consumption is dependent on the raw materials and process used and is approximately 3-6.5 GJ of fuel per ton of clinker, which accounts for 30-40% of the production costs (WBCSD, 2005). The heat intensity of the kiln provides a unique source for conventional and industrial waste disposal. While the primary fuel source is coal, the kiln utilizes substitute fuels, for example solvents, oils, tires, carpets, organic and other hazardous wastes (Choate, 2003). The utilization of substitute fuels varies globally, however it is an area that is increasingly explored to reduce non-renewable fuels, as well as landfill waste. The emissions from the use of substitute fuels need to be addressed to assess the impacts.

2.1.3 Carbon Capture and Storage

Carbon capture and storage (CCS) aims to reduce CO_2 emissions in cement by utilizing different chemical processes (Naranjo et al., 2011). In the cement industry, CCS is of increasing interest due to the significant emission from manufacturing. Two types of technologies are typically explored: oxy-combustion and post-combustion capture (Barker et al., 2009). These processes are effective at reducing emissions, however current technology is cost-prohibitive and requires further demonstration to be adopted by the industry. An alternative is to combine the production of cement with power generation.

In addition to CCS, calcium carbonate looping (CaL) captures waste CO_2 from energy production which can then be used in cement manufacturing (IEAGHG, 2014). The process creates a waste by-product, calcium oxide (CaO), that can then be used as a raw material in cement production. The process requires the development of CCS and the infrastructure to connect the power and cement plants, which is often difficult due to already established locations. This example of industrial ecology is the type of innovation the industry needs to reduce the impact of manufacturing. Furthermore, use of supplementary materials as a replacement for cement offsets the associated impacts.

2.2 Supplementary Cementitious Materials

Cement utilizes a significant amount of raw materials, approximately 1.6 tons per ton of cement. Supplementary cementitious materials (SCM) reduce the impact of cement through utilization of other waste stream products (Siddique and Kunal, 2016). The use of SCM has significant environmental advantages in that it utilizes a waste product and reduces energy usage. Some examples are pozzolans, which are obtained as industrial by-products. A pozzolan is a siliceous material which in fine powder form reacts with calcium hydroxide and moisture to form a cementitious material (King, 2005). These materials are used to replace a percentage of the cement in the concrete mix. Fly ash and ground granulated blast furnace slag are commonly used in concrete design mixes to offset cement.

2.2.1 Fly ash

Fly ash is produced from the combustion of coal and obtained from electric power generation plants. Fly ash has high quantities of reactive silica and has been classified by calcium oxide content. Fly ash does not require pyro-processing and thus reduces not only solid waste but also energy use (Choate, 2003). Practice has shown that fly ash can substitute 15% to 35% cement and concrete mixes have been researched utilizing 70% to 100% volume fly ash.

The advantages of using fly ash also include enhanced design properties. Incorporation of fly ash into the design mix reduces the water required, increasing workability and pumpability (King, 2005). In comparison to Portland cement, fly ash cement takes longer to gain strength and cure due to the lack of bleed water, which also reduces the rate of hydration and plastic shrinkage (King, 2005). Quality control of the cement is difficult due to the varying sources and properties of the fly ash.

The use of fly ash is specified in different percentages in concrete standards. The interest in fly ash is increasing in developing countries like India, where the government has established requirements to utilize the coal by-product in generation of cement and to prevent landfills (WBCSD, 2002). Additional industrial by-products, such as blast furnace slag, can also be utilized.

2.2.2 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag, or slag, is generated from the steel manufacturing process, formed when molten blast-furnace slag is rapidly chilled in water (Meyer, 2002). New techniques have been developed to reduce the energy required to use slag in cement, where the furnace slag is directly injected into the raw mix. The slag bonds with the other additives in the kiln forming a material similar to clinker. The process is advantageous in terms of reduced raw materials, as well as reduced energy costs due to lower moisture content. When used to replace cement, approximately one ton of slag can offsets a ton of CO_2, due to utilization of the waste product.

2.2.3 Natural Pozzolans

Fly ash and slag are sourced from industries with potentially finite lifespans. If production diminishes, the industry will no longer be able to source these established materials in the same quantities. Natural alternatives are increasingly explored as replacements. Materials such as calcined clay, calcined shale, and metakaolin, have properties, once heated, which allow for partial replacement of cement. The use of these natural pozzolans, however, still requires calcination that requires energy and leads to additional emissions.

Agricultural waste, such as wood ash, rice husk ash (RHA) and sugar cane bagasse have been shown to have properties similar to highly active pozzolans (i.e. Siddique and Kanal, 2016). These products are often burned on-site for energy. The generated ash represents a low-value waste material that has potential as a partial replacement for cement. While integration of these materials will increase the sustainability of concrete, further work is needed to evaluate performance and develop new methods of design and construction.

3 Design and Construction

3.1 Innovative design

Optimization of the design and construction of concrete structures is an area of innovation in the industry. Examples include pre-cast structural systems and flexible fabric formwork. Precast technology is an example of offsite construction that is an established sector that would benefit from streamlined construction process and development of integrated structural systems (Holton et al., 2010). Precast components have the potential to provide structural components that provide advances in energy efficiency through increased building envelope performance.

Fabric formwork is a process that also aims to streamline the construction process. The method is most notably known for casting concrete in thin shells, utilizing the flexibility of the formwork to create the desired curvature (Veenendaal et al., 2011; Veenendaal and Block, 2014). The method integrates structural efficiency and architectural aesthetics. Fabric formwork concrete has more recently been shown to be a feasible method for the construction of optimized, non-prismatic, structural components (Orr et al., 2011).

The benefits of flexible formwork include reduced material, embodied water, as well as on-site construction waste (Ibell et al., 2013; Orr et al., 2011). The use of fabric formwork has also been shown to reduce the depth of carbonation (Orr et al., 2011). Carbonation of concrete is well-documented, in which the calcium hydroxide in the material reacts with CO_2. The process reduces the pH of the concrete, thereby decreasing the passive layer of that protects the steel reinforcement from corrosion, decreasing durability. Through an innovative design approach, fabric formwork is increasing the sustainability of concrete on multiple levels.

3.2 Increased Lifespan

Concrete structures are often designed to have a 100-year lifespan, however degradation of the material can lead to shorter life spans, typically needing repair or replacement within 40-60 years or less. The primary cause of degradation is cracking due to a variety of factors. Cracks allow for increased permeability leading to corrosion of the reinforcement and subsequently decreased structural capacity. Self-healing concrete aims to extend the lifespan by closing cracks that lead to degradation of the structure. A variety of approaches are used, such as micro-encapsulation, bacterial healing, shape memory polymers and vascular networks (Lark et al., 2013). Through integration of innovative healing approaches and increased focus on lifetime design, the lifespan of concrete structures can be extended. Could also mention concrete is relatively inert e.g. the Pantheon (unreinforced concrete) has been around for 2000 years and still standing.

4 End of Life

4.1 Recycled Aggregate

At the end of life of a structure, the concrete can be crushed into aggregate that can reused to increase the sustainability of the material. The quality of the material is lower than new aggregate, which suggests a shorter lifespan of the structure due to bonding issues. Some researchers claim that the recycled aggregate requires additional cement to be used therefore the material is not of any benefit (Allwood and Cullen, 2012). However similar to recycled plastics, the reuse of the material lowers the impact of the industry. Studies have shown that comparable compressive strengths can be achieved using recycled aggregate (Levy and Helen, 2004). In addition to recycling, the carbonation of concrete, which is problematic in a reinforced concrete structure, can be beneficial to any recycled aggregate. For example, when used as road-bed gravel, the carbonated material has potential to serve as a carbon sink (Collins, 2010). Overall, the reuse of concrete as aggregate extends the lifespan and reduces the need for raw materials, thus reducing total impact.

4.1.1 Plastic

Incorporation of waste by-products to off-set raw materials aims to increase the sustainability of concrete. Recycled plastic has been shown to be used in concrete in various forms to offset solid waste that would be landfill (Siddique et al., 2008; Saikia and de Brito, 2012). In non-structural concrete, the use of pulverized and shredded plastic can serve as a replacement for sand and stone aggregate (Savoikar et al., 2015). The influence of plastic aggregate needs to be further investigated to understand the effects on workability, the interface between the paste and plastic, and overall strength to be developed in a structural material. Development of innovative materials are needed to increase the sustainability of concrete and the built environment.

5 Summary

Concrete is consumed globally and demand is increasing with growth in developing countries. Although the embodied energy of concrete is considered to be low per unit weight, the primary constituent of concrete, cement, has a significant impact on the environment. Cement manufacturing is an energy intensive process that consumes significant amounts of raw materials and emits large amounts of CO_2. Reducing the impact of cement focuses on substitution of nonrenewable fuels and development of supplementary cementitious materials.

To reduce the embodied energy of cement, the manufacturing process must be examined in terms of a closed-loop cycle that has minimal input and output. The cement industry currently utilizes substitute fuels, however the primary energy source remains to be coal. Waste fuels provide a reduction in nonrenewable fuel usage and the volume of landfill materials. Further, direct substitution of cement with supplementary cementitious material, like fly ash, reduces the quantity of cement needed thereby offsetting the raw materials and energy used while making use of waste by-products.

A multi-level approach is required to increase the efficiency of the material. Industrial ecology aims to utilize waste products generated by other manufacturing processes to create a symbiotic relationship between the cement plant and the surrounding industries. The process utilizes emissions and industrial by-products to create a zero waste process.

New methods of design and construction can also increase the sustainability of concrete through optimization of structural components and in service performance. Increased durability will also allow for longer lifespans and reduce repair and replacement costs, which are substantial. As with any innovation in the construction industry, there are barriers to adoption, however, the topics discussed briefly here are examples of ways in which to increase the sustainability of concrete.

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